METHOD AND DEVICE FOR STATE SENSING OF TECHNICAL SYSTEMS SUCH AS ENERGY STORES

Field of the Invention

The present invention relates to a method for state sensing of a technical system, particularly an energy store, in which performance quantities are measured and supplied to a state estimation routine, which determines the state variables characterizing the current system state using a model based on system-dependent model parameters and the measured performance quantities, the measured performance quantities and possibly the determined state variables additionally being able to be supplied to a parameter estimation routine, which in turn determines the model parameters depending on the use by estimation, to improve the state estimation. The present invention further relates to a corresponding device and a computer program for carrying out the method as well as a computer program product.

Background Information

A method of this class for battery state identification is described in German Patent Application 199 59 019.2. Proceeding from measurable performance quantities, such as current, voltage, and temperature, state variables are determined in this case by estimation using a model, which is implemented in the form of a (Kalman) filter. Since the parameters of the model can change due to aging of the battery as well as through possible suddenly occurring defects, a parameter estimation routine is additionally provided in order to also track these parameter changes online and be able to adjust the parameters appropriately. The current parameters are then supplied to the state estimation routine, i.e., the filter. In this way, the model is continuously adapted to the

actual state of the battery and the filter does not estimate any incorrect values for the state variables. The separation of the estimation of state variables and parameters by the filter and the parameter estimator, respectively, causes biased estimations to be avoided and/or to become improbable.

It has been shown that the method described for state identification using estimation of both the state variables and the model parameters they are based on is frequently not sufficient to guarantee a required accuracy of the estimated values and to avoid divergences in the covariance matrices frequently used for estimation.

It has therefore been endeavored to design the state and parameter estimation more stably with computing and memory needs reduced as much as possible and to allow such an estimation for all conceivable system states.

Advantages of the Invention

In the method according to the present invention, only specific state variables and/or parameters are used at any time for estimation, this selection being performed on the basis of the dynamic response of the measured performance quantities. A device according to the present invention therefore has means for determining the dynamic response of the measured performance quantities, for example means for producing the temporal gradients of the respective performance quantities, as well as selection means, through which specific state variables and/or parameters are determined from the corresponding estimation routine. Such selection means may, for example, be implemented in the form of tables, stepped functions, or threshold value functions, through which specific parameters and/or state variables are assigned to specific dynamic ranges of the performance quantities.

Kalman filters, which operate with covariance matrices of the estimated quantities, are frequently used for state estimation. Covariance matrices represent the root-mean-square deviation of the estimated value from the measured value on their diagonals, and the remaining matrix elements represent the correlations between the individual state variables. Through the method according to the present invention, the order of these matrices is reduced, and thus the numerical outlay and the necessary storage requirements are diminished. Those parameters which change in different time ranges and in the event of different excitations, i.e., in the event of the performance quantities present, may also henceforth be determined better.

It is advantageous to estimate those state variables and/or parameters which have small time constants at a high dynamic response of the measured performance quantities, and to estimate those having large time constants at a low dynamic response of the measured performance quantities. Meanwhile, the respective other state variables and/or parameters are maintained or tracked using a predetermined model.

In the example of battery state identification, a battery model uses various resistance and voltage quantities having different time constants. Ohmic values and charge-transfer overvoltage have small time constants and are preferably estimated when the measured performance quantities have a large dynamic response. In contrast, the concentration overvoltage, for example, has a large time constant, so that this quantity may be estimated at a low dynamic response. The respective other quantities are to be maintained during the estimation or changed according to a predetermined pattern.

It is further advantageous if it is determined before the estimation determination whether the system is in a limit state and if the state variables and/or parameters are only estimated if the system is not in such a limit state. These

types of limit states exist, for example, at the beginning and the end of the service life of a technical system. In the example of battery state identification, this means that in a situation in which the battery is almost fully charged, more accurate estimated values may be dispensed with, since this limit state is a desirable and non-critical area. Another case exists if the battery is in a very poor (charge) state. Since this is normally recognized sufficiently early and therefore complete failure of the battery may be avoided, this limit state is also not of special relevance.

Through this masking out of the estimation in the boundary areas of model accuracy, divergences of the filter/estimator and poor qualities of the quantities determined are avoided. If, for example, the charge state of a fully charged battery worsens again, the battery automatically enters an operating point in which the model used has full validity and a Kalman filter may provide estimated values of greater quality. Advantages also result in regard to the hardware necessary. Lesser numerical complexity is thereby achieved, and thus a lesser utilization of the processor and lesser demands for the storage requirements in the RAM.

In the method according to the present invention, it is further expedient to check the quality of the estimation determined on the basis of a covariance matrix mentioned above. Specifically, the smaller the value in this covariance matrix for the respective state variable, the more probable or more accurate the estimated value of this quantity. The same applies for parameter estimation. In this case as well, there are covariance matrices in the typical estimation theories (e.g., Bayes, maximum likelihood methods), which make an assertion about the quality of the parameter estimation and/or the accuracy of the estimated parameter. The approach is about the same here as for the state estimator. The convergence (to values near zero) of the matrix quantities assigned to the estimated quantities may be used for the purpose of rating the

quality of the estimation. In addition, with appropriate weighting of the results determined, the overall assertion in regard to the state variables, such as charge and aging state of the battery, may be enhanced even more.

A simple way for determining the quality of the estimation is to fix a threshold value for the matrix value assigned to the respective estimated quantity. These threshold values are determined by experimental values and are near zero as a rule.

If the estimated values only have low quality, other "backup" methods may also be included in the evaluation, and may be more strongly weighted. Using this type of "backup" method, the respective quantities are maintained or adjusted according to simple models which do not lead to divergences. On the other hand, it may be decided, for example, momentarily not to accept certain parameters from the state estimation routine or that momentarily certain states may not initiate the parameter estimation routine.

The invention is described in the following with reference to an exemplary embodiment illustrated by the attached drawing.

Figure 1 shows the schematic layout of the components of a device according to the present invention for state sensing of an energy store.

Figure 2 shows a schematic example of the convergence of a state variable and the associated covariance.

Figure 3 shows a schematic example of the divergence of an estimated state variable and the associated covariance.

Figure 4 shows a flow diagram of an exemplary embodiment of the method according to the present invention.

Figure 5 shows a flow diagram for determining the quality of the estimated quantities.

The present exemplary embodiment may be read as state sensing for energy stores such as automobile batteries, but is not restricted to this.

In Figure 1, the components for state sensing according to the present invention of an energy store 1, such as an automobile battery, are illustrated schematically. A sensor and measurement unit 2 performs measurements of performance quantities x, such as current, voltage, and/or temperature, on battery 1. The measured performance quantities are supplied via lines 7 to a state estimator 3, which, for example, determines state variables, which characterize the current system state, in a known way using a Kalman filter. Such state variables a may be the available charge or the age of battery 1. State estimator 3 utilizes a model in which measured performance quantities x are entered to determine these state variables a. The model itself operates with model parameters p, which are also dependent on the aging processes of energy store 1. In order to avoid the model losing its validity due to changed parameters p, model parameters p are updated using a parameter estimator 4. For this purpose, a parameter estimation routine is used, which uses measured performance quantities x and possibly additionally estimated state variables a as input quantities. Updated parameters p are then delivered to state estimator 3. For this purpose, state estimator 3 and parameter estimator 4 are connected to one another.

State variables a determined by state estimator 3 are processed further in order to take currently favorable measures (for example, charge state displays, modification of the energy supply).

Figure 1B shows a design practically suitable for state estimator 3 and parameter estimator 4, in which the individual components for state sensing according to the present invention are each present assembled into one unit. Measured performance quantities x are supplied via lines 7 to state estimator 3 and/or parameter estimator 4. Subtractors or differentiators, which produce the gradients of one measurement quantity x at a time, are used as means 8 for detection of the dynamic response of measured performance quantities x. A selection unit 9, which selects state variable a and/or parameters p to be subsequently estimated depending on the detected dynamic response of these performance quantities x, is connected downstream. Selected performance quantities x are supplied at state estimator 3, together with updated parameters p, to a computation unit 10, which computes specific state variables a using a model. Most estimation models operate with covariance matrices, whose values assigned to the individual state variables converge toward zero if the estimated value approximates the real value over time. These matrix values (covariances) may therefore be used for rating the quality of the estimation.

To rate the quality of the estimation, threshold values associated with the respective covariances are, for example, fixed in a unit 11 and the quality of the estimation is determined by subtraction of the estimated value from the fixed threshold value. If, for example, an estimated state variable does not fall below this threshold value after a predetermined number of cycles, it is possible to reject the estimated value and maintain the previously estimated value instead. In this way, it is possible to prevent increasing deterioration of the estimation.

Further characteristics and further capabilities of the invention result from the following Figureures.

Figure 2A shows an example of a rapidly converging estimated state variable a(3), which is not subject to any fluctuations after convergence. Such state variables, such as the concentration overvoltage, have large time constants. The associated matrix element of the covariance matrix illustrated in Figure 2B, in this case K(3,3) to a(3), i.e., the covariance to this state variable, converges rapidly toward zero. To check the quality of the estimation, it is possible to fix a threshold which is to be reached after a certain number of cycles, i.e., a number of iterative estimations. If this is not the case, the estimation for this state variable may be rejected.

An example of a divergence of a current state variable ã(1) and associated estimated value a(1) is shown in Figure. 3, the fluctuating time curve of current state variable ã(1) and estimated state value a(1), which moves away from the zero line over time, being illustrated in Figure. 3A below the zero line. Associated covariance K(1,1) to state variable a(1) reflects that this estimation is not suitable. The covariance does not converge, but increases continuously over time, as illustrated in Figure. 3B.

Cases such as that shown in Figure. 3 are avoided by the present invention in that if the quality of the estimation is not sufficient, "backup" methods are utilized.

Figure 4 shows the flow diagram of an exemplary embodiment of the method according to the present invention. At the beginning of the estimation method, first a specific time T_{min1} is allowed to pass until the system has assumed a state suitable for state estimation, before the actual estimation method begins. Subsequently, the dynamic response of the excitation, i.e., the dynamic response of measured performance quantities x, is scanned (S1). These are, for example, the time-dependent quantities current, temperature, and voltage. If, for example, the discharge current of the battery remains

nearly zero over a relatively long period of time, since, for example, the consumer is completely supplied by the generator, it is not to be expected from this that specific state variables a or parameters p dependent on the current will be subject to change. Further measurement values are then awaited, until a further time interval T_{min2} has passed (S2).

If a dynamic response of the measured performance quantities begins, the quantity of this dynamic response is scanned (S3). For a low dynamic response of the measurement values, it is first determined whether the system is in a limit state or boundary region (in batteries, for example, the fully charged or drained state). The same scanning also occurs in the case of a large dynamic response of the measured performance quantities (S4 and/or S5).

If the system is not in a boundary region, the actual estimation of the state variables may be started. According to the present invention, at a low dynamic response of the measurement values, the state variables having small time constants are maintained (S6), while the state variables having large time constants are estimated (S7). In contrast, for measurement values having a large dynamic response, the state variables having large time constants are maintained (S8), while the state variables having small time constants are estimated (S9). In the battery model used here, as already mentioned, the ohmic values and the charge-transfer overvoltage represent state variables/parameters having small time constants, while, for example, the concentration overvoltage represents a state variable having large time constants. According to the present invention, those parameters and state variables which are not expected to cause changes in the dynamic response of the system are not redetermined by estimation. In this way, enlarging inaccuracies during the estimation due to unnecessarily frequent estimations, which could then invalidate the model or provide incorrect state results, may be avoided.

If, during the check (S4, S5) as to whether the system is in a limit state (boundary region), it is determined that this is the case, the state variables/parameters are, for example, maintained or evaluated using "backup" methods (S10, S11) to avoid incorrect estimations (boundary regions of the model accuracy). These types of methods are based on stable models in which no divergence is to be expected.

After the routine shown in Figure 4 is finished, one cycle of the state estimation according to the present invention has ended and further cycles may follow immediately or with delays, which are to be fixed.

Figure. 5 shows a flow diagram for determining the quality of the estimation described above. For this purpose, first an easily measurable quantity, which is calculated from estimated quantities, is compared with the quantity actually measured (T1). In the event of good correspondence (for example of the estimated and measured battery voltages), the convergence of the covariances associated with the state variables/parameters is checked (T2). Specifically, it is possible that individual covariances have not yet sufficiently converged (see also Figure 2B), so that in this case a specific typical convergence time T_{min} still has to be awaited (T3) until sufficiently good convergence results. When this is the case, the estimated state variables/parameters are evaluated (T4) and from this, for example, the charge state or the age of the battery is determined.

In contrast, if the time T_{min} has already passed without the associated covariances having sufficiently converged, i.e., for example, having passed below a specific threshold value, the estimated quantities are rejected and the parameter estimation routine and/or the state estimation routine (Kalman filter) is restarted (T5). Until the reestimated quantities are received, simple "backup" methods are utilized (T6).

If there is no sufficient correspondence between an easily measurable and estimable reference quantity (for example battery voltage) from the beginning, the covariance matrix may also not be sufficiently converged. This result may be rechecked after a time period $T_{min}*$ (T7). If this result remains unchanged, the parameter and/or state estimation is also restarted (see Figure 4) and "backup" methods are utilized (T8, T9).